

# Clustering of Local Group distances: publication bias or correlated measurements? II. M31 and beyond

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## ABSTRACT

The accuracy of extragalactic distance measurements ultimately depends on robust, high-precision determinations of the distances to the galaxies in the local volume. Following our detailed study addressing possible publication bias in the published distance determinations to the Large Magellanic Cloud (LMC), here we extend our distance range of interest to include published distance moduli to M31 and M33, as well as to a number of their well-known dwarf galaxy companions. We aim at reaching consensus on the best, most homogeneous, and internally most consistent set of Local Group distance moduli to adopt for future, more general use based on the largest set of distance determinations to individual Local Group galaxies available to date. Based on a careful, statistically weighted combination of the main stellar population tracers (Cepheids, RR Lyrae variables, and the magnitude of the tip of the red-giant branch), we derive a recommended distance modulus to M31 of  $(m - M)_0^{\text{M31}} = 24.46 \pm 0.10$  mag—adopting as our calibration an LMC distance modulus of  $(m - M)_0^{\text{LMC}} = 18.50$  mag—and a fully internally consistent set of benchmark distances to key galaxies in the local volume, enabling us to establish a robust and unbiased, near-field extragalactic distance ladder.

*Subject headings:* astronomical databases — distance scale — galaxies: distances and redshifts — galaxies: individual (M31, M32, M33, NGC 147, NGC 185, NGC 205, IC 10, IC 1613)

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## 1. Introduction

The accuracy of extragalactic distance measurements ultimately depends on robust, high-precision determinations of the distances to the galaxies in the Local Group. This is, of course, the basis of the concept of the astronomical “distance ladder” (for an up-to-date, modern version of the distance ladder, see de Grijs 2013). In particular, distance measurements to the Large Magellanic Cloud (LMC) have played an important role in constraining the value of the Hubble constant,  $H_0$ . The *Hubble Space Telescope* (HST) Key Project (HSTKP) on the Extragalactic Distance Scale (Freedman et al. 2001) estimated  $H_0 = 72 \pm 3$  (statistical)  $\pm 7$  (systematic)  $\text{km s}^{-1} \text{Mpc}^{-1}$ . Most notably, the  $\sim 10\%$  systematic uncertainty affecting their determination of  $H_0$  was said to be predominantly driven by the remaining systematic uncertainties in the assumed distance to the LMC prevalent at that time (Freedman et al. 2001; Schaefer 2008; Pietrzyński et al. 2013).

Yet, the accuracy of LMC distance determinations has been dogged by persistent claims of “publication bias” (e.g., Schaefer 2008, 2013; Rubele et al. 2012; Walker 2012). Therefore, in de Grijs et al. (2014; henceforth Paper I) we re-analyzed the full body of LMC distance measurements published between 1990 and 2013. We concluded that strong publication bias is unlikely to have been the main driver underlying the clustering of many published LMC distance moduli. However, we found that many of the published values were based on highly non-independent tracer samples and analysis methods. In turn, this has led to significant correlations among the body of LMC distances published since 1990. The earlier conclusion that the tight clustering of published values and the reduction in the spread observed in recent years may have been due to publication bias was, in essence, based on inappropriate application of the Kolmogorov–Smirnov (KS) test to a data set that ultimately did not meet the requirements for such tests: KS tests are only applicable to samples that consist of independent and identically distributed values. In the context of LMC distance measurements, both constraints are violated. These violations originate, in particular, from progress in data analysis, enlarged tracer samples, and improvements in both our theoretical understanding and in the model implementation of theoretical stellar evolution scenarios, which all drive down the uncertainties in the derived parameters (including distance moduli) and lead to more consistent results.

We now extend our distance range of interest to include published distance moduli to M31, a few of its companion galaxies, and a few other well-known Local Group members in order to assess whether or not these measurements may be affected by publication bias or correlations among the methods employed to obtain them (cf. Dalcanton et al. 2012). More importantly, however, we aim at reaching consensus on the best, most homogeneous, and internally most consistent set of Local Group distance moduli to adopt for future,

more general use. Combined with the results of Paper I, we aim at determining whether the distance scale in the Local Group as a whole may need further revision. The present series of papers is based on the largest set of distance determinations to Local Group galaxies available to date, which we have assessed carefully in the context of an analysis of population-specific properties and biases never done to the same extent. This paper is organized as follows. In Section 2 we outline our approach to compiling our database of distance measurements. In Section 3 we explore in detail the trends, if any, in the distance measurements to M31. We pay particular attention to the calibration relations used to arrive at the M31 distances based on variable star tracers: see Section 4. We subsequently focus our analysis on a number of M31 companion galaxies, as well as a few other well-known Local Group members (Section 5). Finally, in Section 6 we summarize and place our results in the broader context. We conclude with our recommendations as to which distances to Local Group galaxies constitute a homogeneous, internally consistent set.

## 2. Distance Measurements to the M31 Group

### 2.1. M31 distance determinations, 1918–2013

To compile our M31 distance database, we relied entirely on the NASA/Astrophysics Data System (ADS) compilation of the published literature, in the absence of suitable comprehensive databases we might use as our basis (but see Vilardell et al. 2006). We checked all of the nearly 13,000 articles published as of late January 2014 and which contained references to M31 in the NASA/ADS compilation for references to newly determined distances to the galaxy. Our comprehensive search resulted in a total of 168 distance measurements to M31 or components associated with the galaxy’s main body. We did not include determinations of the distances to the large population of accompanying dwarf galaxies (but see Section 2.2). Only very few ( $\sim 5$ ) of the more recent determinations include separate analyses of the statistical and systematic uncertainties in the published measurements. Our final database, sorted as function of both publication date and distance tracer, is available from <http://astro-expat.info/Data/pubbias.html>. Its structure is similar to that used for our LMC distances database presented in Paper I.

Among the 117 newly determined distance moduli published since 1990, which we take as the period of interest for our main analysis, only three appeared in non-refereed publications. For the same reasons as justified in Paper I, we opted to retain these measurement so as to avail ourselves of a complete publication record. Three articles (Rich et al. 2005; Mackey et al. 2006; Perina et al. 2009) reported distance measurements to individual globular clusters (GCs) associated with M31. We calculated the average values for each of these three data

sets (containing 19, 4, and 11 GCs each, respectively), which we will use for further analysis in the remainder of this paper. Specifically, we obtained  $(m - M)_0^{\text{M31}} = 24.49 \pm 0.15$  mag,  $24.40 \pm 0.16$  mag, and  $24.42 \pm 0.21$  mag for the mean distances based on the individual GC measurements reported in Rich et al. (2005), Mackey et al. (2006), and Perina et al. (2009), respectively. The uncertainties quoted above reflect the spread among the individual GC distances (i.e., the depth of the M31 GC system), as well as the typical photometric uncertainty, which we added in quadrature.

## 2.2. Published distances to selected additional Local Group galaxies

Since we aim at establishing a robust set of benchmark distances within the local volume, we selected a number of additional Local Group members of different types. In addition to the third largest spiral galaxy in the Local Group, M33, we selected M31’s close, late-type companion M32 (classified as a compact elliptical-type galaxy), the dwarf spheroidal (dSph)/dwarf elliptical (dE) galaxy pair NGC 147/NGC 185, as well as the dSph/dE galaxy NGC 205 (M110), the dwarf irregular object IC 10, and the irregular galaxy IC 1613. All of these galaxies host a variety of tracers that can be used for accurate distance determinations—each affected by its own systematic uncertainties—and cross-calibration among the different tracers. The inclusion of IC 1613 is particularly interesting from the perspective of metallicity differences: the galaxy’s Cepheids, for instance, are characterized by a significantly different metallicity compared with their Galactic counterparts,  $\Delta[\text{Fe}/\text{H}] \simeq 1$  dex (for a discussion, see e.g. Majaess et al. 2009). The full database of newly reported distance measurements to each of our sample galaxies can be accessed at <http://astro-expat.info/Data/pubbias.html>.

At the time of the completion of our online database, in late January 2014, the NASA/ADS contained 6008 articles that referred to M33, as well as 2256, 576, 758, 1299, 998, and 1057 articles containing references to M32, NGC 147, NGC 185, NGC 205, IC 10, and IC 1613, respectively. Our exhaustive exploration of these  $\sim 12,000$  publications led to inclusion of a total of 131 newly reported distances to M33 since records began in 1926, as well as 38 to M32 (since 1944), and 37, 54, 43, 46, and 145 distance estimates to, respectively, NGC 147, NGC 185, NGC 205, IC 10, and IC 1613. The most commonly available distance tracers include Cepheids (M33, NGC 205, IC 10, and IC 1613) and RR Lyrae (M32, M33, NGC 147, NGC 185, NGC 205, and IC 1613) variable stars, as well as features associated with bright giant stars, such as the level of the tip of the red-giant branch (TRGB; M32, M33, NGC 147, NGC 185, NGC 205, and IC 1613) or the red clump (RC; M32, M33, and IC 1613), and the technique of surface brightness fluctuations (SBFs; M32, NGC 147, NGC 185, and NGC

205; for IC 10, an equivalent approach was taken by Yahill et al. 1977). M33 is the only object among this additional sample of Local Group galaxies for which we have access to two types of independent, *geometric* distance determinations, based on water masers (Greenhill et al. 1993; Argon et al. 1998, 2004; Brunthaler et al. 2005) and on a single O-type eclipsing binary (EB) system (Bonanos et al. 2006; Bonanos 2007, 2008).

### 3. Trends in Distance Determinations to M31?

Figure 1 shows the distribution of published distance moduli, corrected for extinction by their respective authors, since the first bold attempts by van Maanen (1918; with references to earlier work), Lundmark (1919), and Luplau-Janssen & Haarh (1922) to measure a trigonometric parallax to the galaxy. Following subsequent attempts to use galaxy dynamics to derive a distance (Jeans 1922; Öpik 1922), Hubble (1922, 1925a,b, 1929a,b) and Lundmark (1923, 1925; and references therein) were the first to use individual objects in M31 as tracers of the system’s distance as a whole. They used classical novae and Cepheid variable stars, respectively, which were easily accessible with telescopes that were available at the time because of these objects’ intrinsically high luminosities. It is, therefore, not a surprise that to date the largest number of newly reported distance measurements to M31 based on individual tracers (42) are based on Cepheid calibrations.

A casual inspection of Figure 1 reveals that the distance to M31 has been known to within  $\sim 15\%$ , given the sometimes sizeable uncertainties, since the 1960s. The average distance modulus has been slowly increasing until the mid-1980s, when it leveled off near a value of  $(m - M)_0^{\text{M31}} \simeq 24.4$  mag, with a typical uncertainty of  $\lesssim 0.15\text{--}0.2$  mag. In this paper, we are particularly interested in exploring any more recent trends in the average distance modulus, specifically during the “modern” period from 1990 until the present time. (The precise choice of starting date of our modern period is not important, provided that we have access to a sufficiently long time span that would allow us to discern any statistical trends.) Therefore, we will not discuss the M31 distance tracers based on nova- or supernova-related light-curve features, since all of the latter were published prior to 1990. In the remainder of this and in the next section, we will examine whether the individual distance moduli published during this period may have been based on either correlated data or model approaches, or perhaps been subject to publication bias.

We follow a similar approach as in Paper I. In Figure 2 we expose our time-restricted data set to further scrutiny. The top panels in this figure show the annual and biennial averages (as well as the number of data points considered) of all distance measurements pertaining to the full period from 1990 until 2013. We specifically highlight the levels of the distance

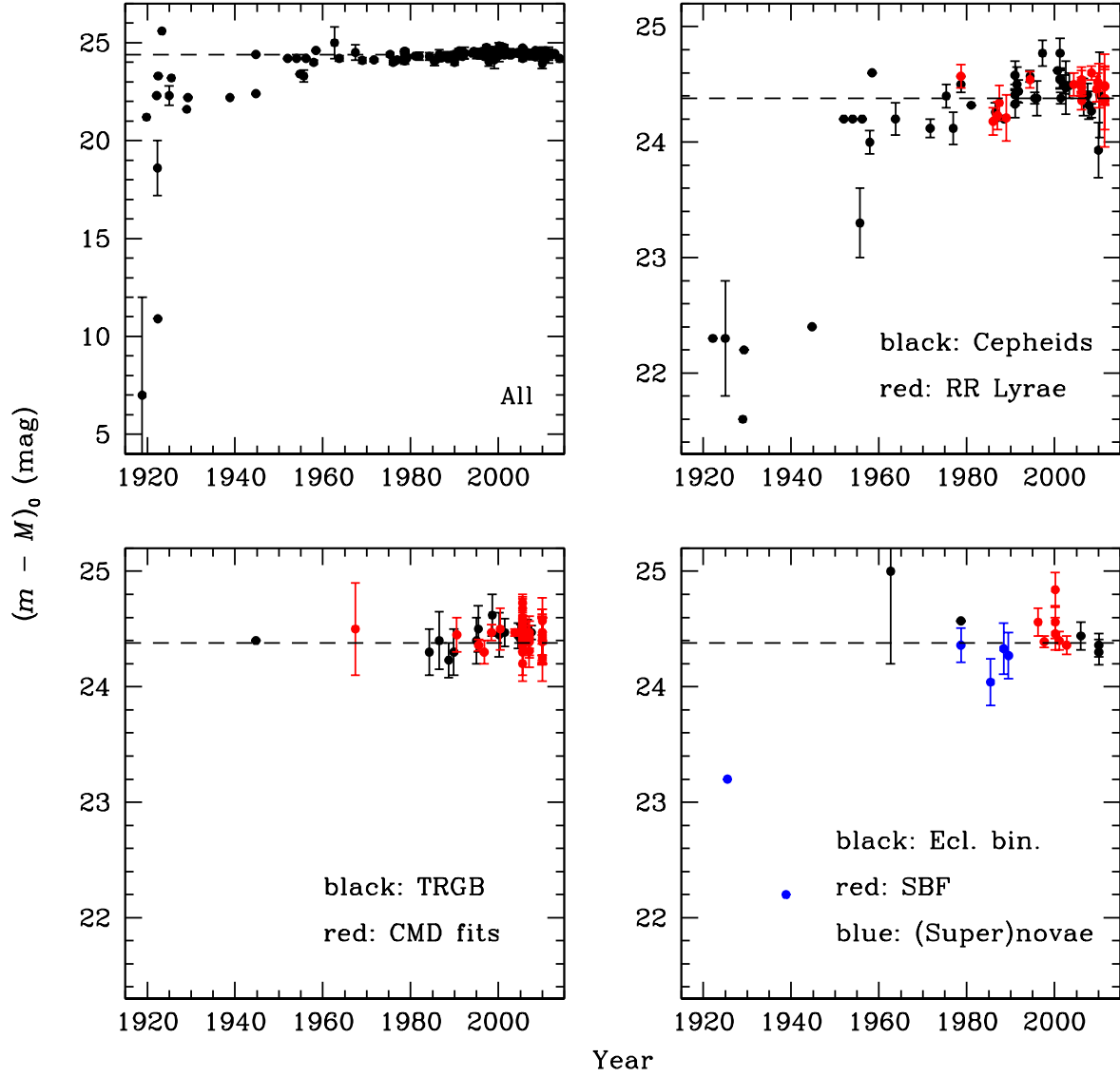


Fig. 1.— Published extinction-corrected M31 distance moduli since records began as a function of publication date (year+month), where possible centered on the galaxy’s center. The horizontal dashed lines indicate the “canonical” distance modulus of  $(m - M)_0^{\text{M31}} = 24.38$  mag (Freedman et al. 2001). TRGB: tip of the red-giant branch; CMD: color–magnitude diagram; Ecl. bin.: eclipsing binary systems; SBF: surface brightness fluctuations.

moduli determined by Freedman et al. (2001), i.e., the “canonical” distance modulus of  $(m - M)_0^{\text{M31}} = 24.38$  mag, and that of McConnachie et al. (2005),  $(m - M)_0^{\text{M31}} = 24.47$  mag. We will use these determinations as our benchmarks to assess the occurrence, if any, of publication bias.

The arrows indicate the publication dates of our two benchmark distance moduli, where the colors correspond to the relevant horizontal dashed lines. At first sight, it does not appear that following the publication of either of our benchmark distance moduli the average levels converged to the respective values. Figures 2e through 2h include the individual distance measurements for four types of common distance tracers, i.e., Cepheid and RR Lyrae variable stars, red giants, and color–magnitude diagram (CMD) fits. The individual distance moduli, sorted by tracer, are available at <http://astro-expat.info/Data/pubbias.html>. Except for the red giant-based distances, we do not discern any clear trends among the individual measurements. As regards the red giants, although their average level does not vary significantly as a function of publication year, the associated uncertainties shrink quite significantly from 1990 until the present time. The red giant-based distances in Figure 2g are predominantly based on measurements of the tip of the TRGB magnitude, except for two values based on RC observations. The observed reduction in the distance moduli based on this distance tracer is reminiscent of the situation for the LMC distance moduli based on RC data (Paper I). Of the 10 articles using the TRGB magnitude as their distance tracers, six<sup>5</sup> are based on newly obtained, independent observations. The remaining four articles (Ferrarese et al. 2000; Sakai et al. 2004; Saha et al. 2006; Rizzi et al. 2007) use a subset of observations discussed in the six independent articles; all of these articles base at least part of their analyses on the published data of Mould & Kristian (1986). Their calibration relations are largely independently determined based on either empirical or theoretical (stellar evolution) considerations.

We thus conclude that there is no compelling reason to assume a significant contribution from publication bias to the bulk of present-day M31 distance moduli. We suggest that the observed clustering of the TRGB-based data points is likely related to our improved understanding of the details of stellar evolution. This is corroborated by the notion that the TRGB magnitudes used as calibration benchmarks span a very narrow range in absolute *I*-band magnitude. The main uncertainties associated with the use of the TRGB as a distance indicator are therefore related to the way in which the TRGB magnitude is detected. However, given that modern approaches are based on very large numbers of stars, edge-detection techniques run into few difficulties in this regard. This is exemplified by the small

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<sup>5</sup>Specifically, Morris et al. (1994), Couture et al. (1995), Salaris & Cassisi (1998), Durrell et al. (2001), McConnachie et al. (2005), and Conn et al. (2012).

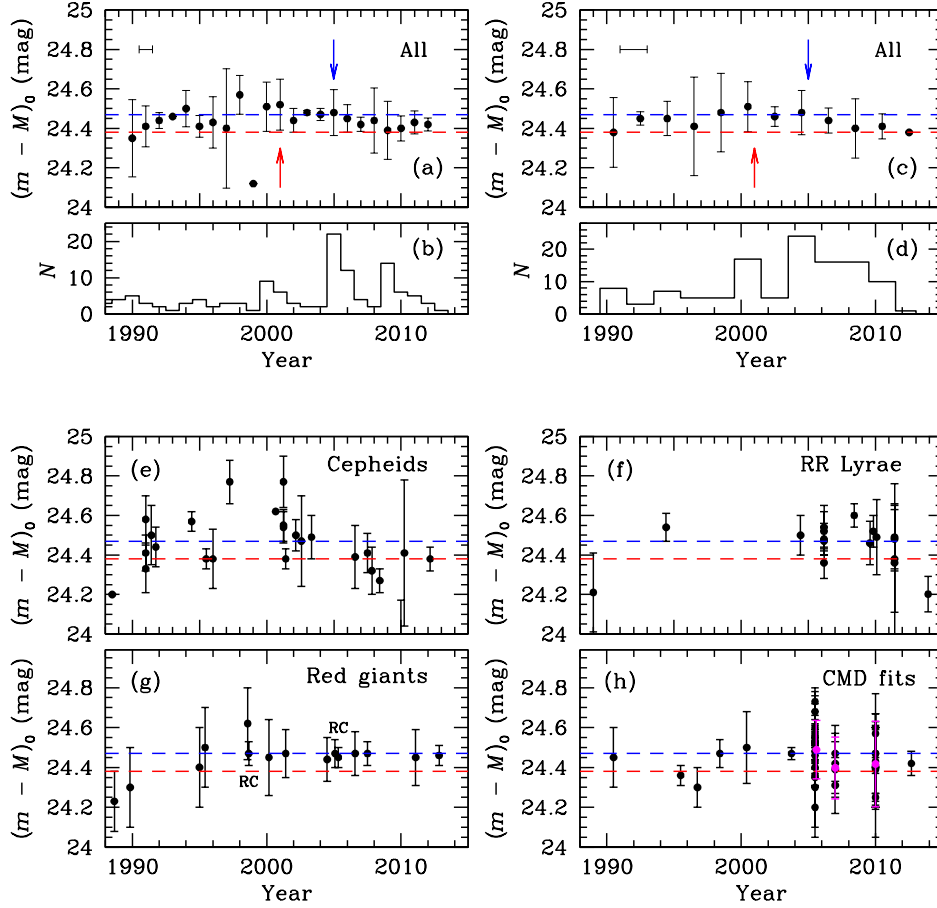


Fig. 2.— Published M31 distance moduli since 1990. (a, b) and (c, d) Annual and biennial average distance moduli, respectively, based on the ensemble of distance tracers of all types, as well as the numbers of distance values considered. The red and blue dashed lines indicate the distance moduli published by Freedman et al. (2001; red arrow) and McConnachie et al. (2005; blue arrow), respectively. The horizontal “error bars” reflect the periods over which the individual data points have been averaged in the respective panels. (e)–(h) Individual distance measurements for the main tracer types. Panel (e) includes all Cepheid-based distances, including those based on classical Cepheids and the Type II Cepheid-based distance modulus of  $(m - M)_0 = 23.93 \pm 0.24$  mag obtained by Majaess et al. (2009). The red giant-based distances in panel (g) are predominantly based on TRGB measurements, except for two values based on red clump (“RC”) observations. The magenta data points with their associated error bars in panel (h) indicate the galaxy-wide averages of the GC-based distance moduli—individually shown in this panel—of Rich et al. (2005), Mackey et al. (2006), and Perina et al. (2009), i.e.,  $(m - M)_0^{\text{M31}} = 24.49 \pm 0.15$  mag,  $24.40 \pm 0.16$  mag, and  $24.42 \pm 0.21$  mag, respectively, where the error bars include the spread among the individual data points as well as the typical photometric uncertainties.



scatter in the resulting distance estimates to M31 shown in Table 1. In the next section, we will examine the distance moduli resulting from the use of period–luminosity relations (PLRs) of variable stars, as well as calibration issues specific to M31 and the converging trends of the average distance moduli over time.

#### 4. Calibration

To assess whether the post-1990 Cepheid- and RR Lyrae-based distance determinations to M31 have been largely independent or instead been subject to significant correlations among data sets, zero-point calibrations, and methods employed, we carefully examined the origins of the individual distance determinations.

We considered 20 publications yielding M31 distance moduli based on Cepheid light curves, as well as eight articles based on RR Lyrae variables (for details, see our online database). Close examination of these 28 papers revealed that more than two thirds (14 Cepheid- and six RR Lyrae-based distance determinations) of recent M31 distance estimates rely on the LMC’s distance as their calibration benchmark. One article, Majaess et al. (2009), reports a distance modulus based on analysis of Type II Cepheid light curves; this distance estimate is discrepant at the  $1.5\text{--}2\sigma$  level with respect to all other modern Cepheid-based M31 distance measurements. This is likely owing to the criterion these authors adopted to distinguish between classical and Type II Cepheids. As they show in their figures 1 and 2, in M31 the transition between the two different types is rather smooth, thus rendering a clear distinction between both Cepheid types uncertain. Because of this issue and the intrinsically different nature of the objects considered by Majaess et al. (2009), we will not include this result in the ensuing discussion. (Note that although Type II Cepheids originate from the same old stellar population as RR Lyrae stars, a comparison of this latter data point with the mean value defined by the RR Lyrae distance moduli leads to a similarly discrepant result.)

Although 12 of the 19 articles based on classical Cepheids use  $(m - M)_0^{\text{LMC}} = 18.50$  mag as their calibration benchmark, the LMC distance moduli adopted by the various authors range from  $(m - M)_0^{\text{LMC}} = 18.42$  to 18.54 mag. This implies that the Cepheid- and RR Lyrae-based distance estimates shown in Figure 1a, c, e, and f are not all based on the same distance scale. We thus proceeded to adjust the distance moduli of all Cepheid- and RR Lyrae-based determinations to a common LMC benchmark of  $(m - M)_0^{\text{LMC}} = 18.50$  mag. For the seven articles whose M31 distance estimates were not based on application of a

relative M31–LMC distance modulus,<sup>6</sup> we checked the LMC distance moduli their resulting distances would be equivalent to (many authors state these values, in fact, while in a few cases this amounted to a simple conversion). Note that the discrepant Type II Cepheid distance modulus of  $(m - M)_0 = 23.93 \pm 0.24$  mag cannot be made more consistent with the distance moduli based on classical Cepheids by adjusting the adopted LMC distance,  $(m - M)_0^{\text{LMC}} = 18.45$  mag, to our benchmark value.

Figure 3 is equivalent to Figure 3, except that we have now “corrected” the relevant distance moduli to a common LMC benchmark modulus of 18.50 mag. Figures 3a and 3c show the size of this effect in the context of the annual and biennial averages. Once again, we do not see any significant trend(s) for either the Cepheid- or the RR Lyrae-based distance determinations, although we note that there may be some hints of publication bias in the results, as reflected by the clustering—above or below the benchmark levels—of data points published close in time (for Cepheid-based distances, cf. the periods between 2000 and 2004, and from 2006 to 2009). In Table 1, we compare the average M31 distance moduli for the comparison period from early 1990 until May 2001 and for two periods following the benchmark publications of Freedman et al. (2001) and McConnachie et al. (2005), for both the original and the “corrected” values. We do not include an average based on RR Lyrae variables for the comparison period prior to the publication of Freedman et al. (2001), since only a single RR Lyrae-based distance estimate was published during that period (Gould 1994), i.e.,  $(m - M)_0^{\text{M31}} = 24.54 \pm 0.07$  mag for  $(m - M)_0^{\text{LMC}} = 18.50$  mag. In Section 6 we will discuss the broader implications of the values listed in Table 1.

## 5. M31 Group Members

We will now discuss the distance estimates pertaining to M33 and IC 1613 separately, because of the fairly large numbers of distance estimates available, followed by a general exploration of the distances reported for the remaining sample galaxies.

### 5.1. Distance determinations to M33 and IC 1613

Figure 4 is equivalent to Figure 1, except that it relates to distance estimates to M33 and IC 1613. Among the different distance tracers available for M33, those based on Cepheids

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<sup>6</sup>*Cepheids*: Feast & Catchpole (1997), Mochejska et al. (2000), Paturel et al. (2002a,b), and Riess et al. (2012); *RR Lyrae*: Sarajedini et al. (2009) and Fiorentino et al. (2010).

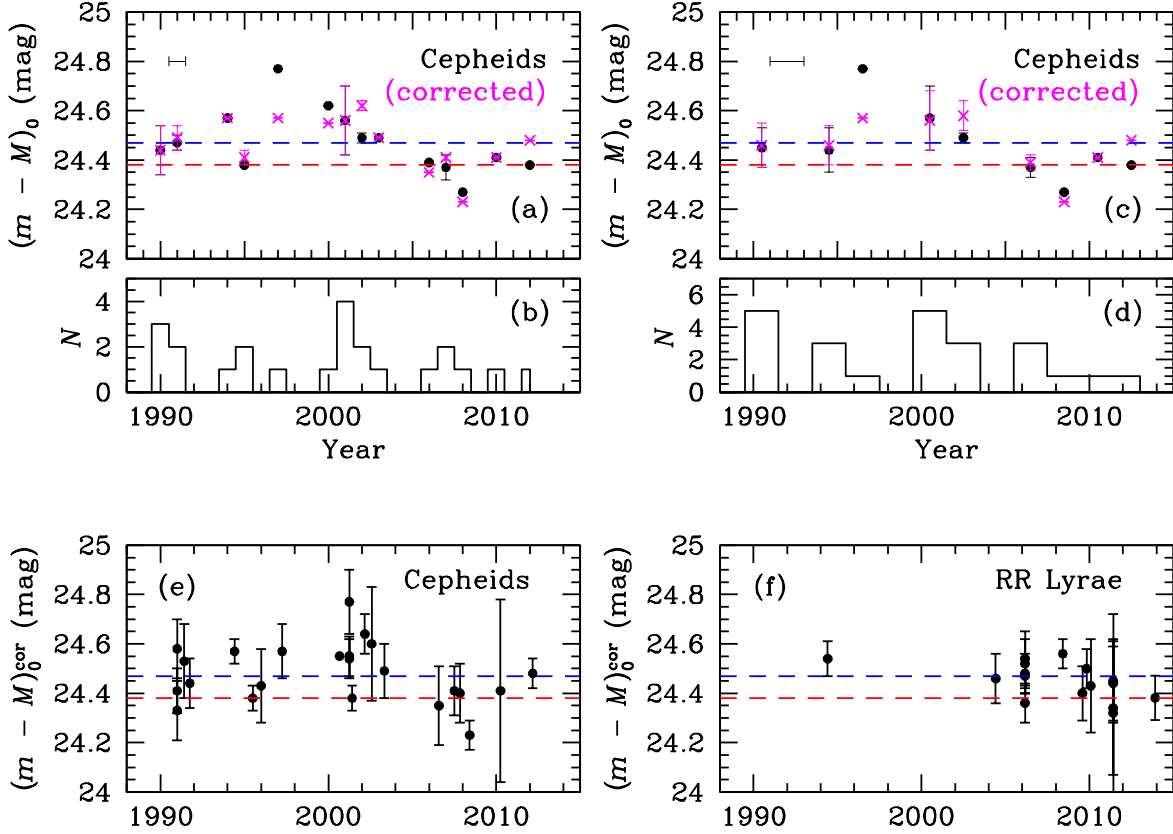


Fig. 3.— As Figure 2, but for the variable star-based distance moduli to M31 only. The magenta data points in panels (a) and (c) have been corrected with respect to the original measurements (black points) to reflect a calibration based on the canonical LMC distance modulus of  $(m - M)_0^{\text{LMC}} = 18.50$  mag. The individual Cepheid- and RR Lyrae-based distance moduli in panels (e) and (f) also reflect this adjustment; panel (e) includes only classical Cepheid-based distance moduli.

Table 1: Statistical properties of the body of M31 distance measurements prior to and following publication of the two benchmark values used in this paper. “Corrected” values refer to distance moduli calibrated to the “canonical” LMC distance modulus,  $(m - M)_0^{\text{LMC}} = 18.50$  mag. Means and population standard deviations are given in units of magnitudes.

		Period					
		00/1990–05/2001 <sup>a</sup>		06/2001–12/2013		02/2005–12/2013	
		Orig.	Corr.	Orig.	Corr.	Orig.	Corr.
All	Mean	24.454		24.435		24.432	
	$\sigma$	0.164		0.110		0.115	
	$N$	42		76		68	
Classical	Mean	24.516	24.502	24.404	24.446	24.363	24.380
Cepheids	$\sigma$	0.140	0.115	0.072	0.118	0.052	0.077
	$N$	14	14	9	9	6	6
RR Lyrae	Mean			24.457	24.443	24.454	24.442
	$\sigma$			0.097	0.072	0.100	0.075
	$N$			15	15	14	14
All variables	Mean	24.517	24.505	24.437	24.444	24.427	24.424
	$\sigma$	0.135	0.111	0.092	0.093	0.097	0.081
	$N$	15	15	24	24	20	20
TRGB	Mean	24.488		24.462		24.467	
	$\sigma$	0.082		0.012		0.006	
	$N$	5		5		3	

<sup>a</sup>including Freedman et al. (2001).

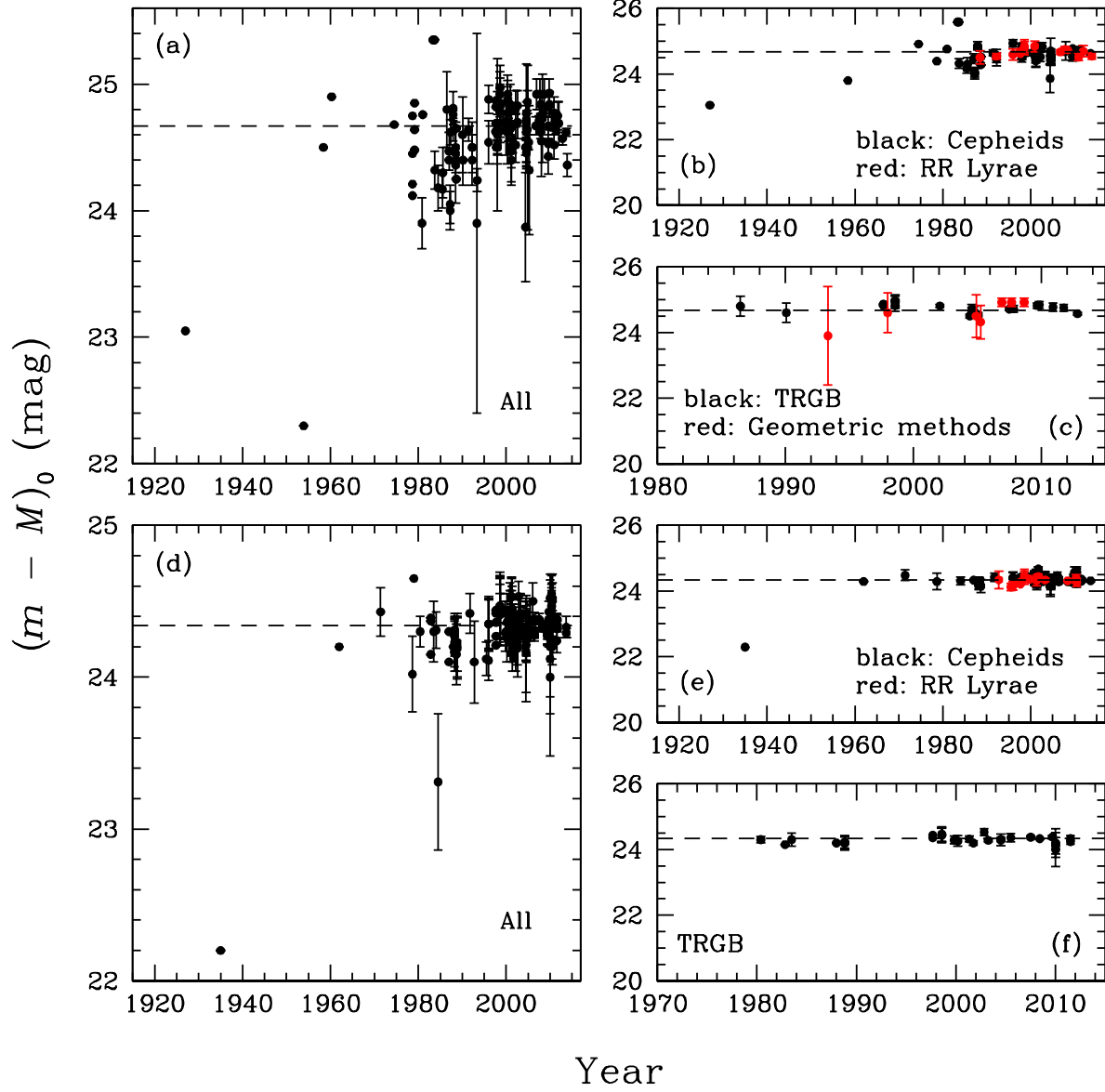


Fig. 4.— As Figure 1, but for (a)–(c) M33 and (d)–(f) IC 1613. The distance moduli based on Cepheids and RR Lyrae variables—panels (b) and (e)—have been corrected to a distance scale defined by a canonical LMC distance modulus of  $(m - M)_0^{\text{LMC}} = 18.50$  mag. The horizontal dashed lines indicate our proposed “best” distance moduli of  $(m - M)_0 = 24.67$  mag (for M33) and  $(m - M)_0 = 24.34$  mag (for IC 1613), respectively (see the text).

( $N = 56$ , of which three are Type II Cepheids), RR Lyrae variables ( $N = 14$ ), and the level of the TRGB ( $N = 20$ ) are most numerous. Similarly, the distance determinations to IC 1613 based on Cepheids ( $N = 84$ ; two Type II measurements), RR Lyrae variables ( $N = 14$ ), and the TRGB magnitude ( $N = 30$ ; including a small number of other giant-based distance determinations published in the 1980s) dominate the total tally. We will thus focus our discussion on these tracers.

As for M31, we first updated the calibration of the distance estimates based on Cepheids and RR Lyrae variables (as well as those based on long-period variables, for M33) relative to an LMC distance modulus of  $(m - M)_0^{\text{LMC}} = 18.50$  mag. Figures 4a and 4d display all distance determinations we collected, without application of any corrections; panels b, c, e, and f show the tracer-specific data sets. We refer the reader to our discussion in Section 6.2 for a detailed analysis of the trends and properties shown in Figure 4.

## 5.2. Comments on our remaining sample galaxies

The other five galaxies in our small sample of Local Group member systems only have between 37 and 54 distance determinations each, in all cases dominated by a small number of tracers. Therefore, we will discuss them jointly in this section. Figure 5 shows the full chronological trends in distance determinations for each of our galaxies (left-hand column), as well as zooms of the more recent timeframe since 1980 (right-hand column). In the latter panels, we have color-coded the distances resulting from the dominant tracer populations: red data points originate from distance measurements based on the TRGB method, blue points come from variable stars (RR Lyrae variables; Cepheid-based distance estimates for IC 10), and green points represent estimates based on the SBF method. The latter was originally developed on the basis of (ground-based) observations of M32 (Tonry & Schneider 1988), although more recent estimates use *HST*-based imaging observations at red optical or near-infrared (NIR) wavelengths (cf. Ferrarese et al. 2000). Except for the 13 SBF-based data points for M32, we also have two such data points for both members of the NGC 147/NGC 185 galaxy pair (Tonry et al. 2001; Tully et al. 2008). We will discuss the implications of the trends and properties seen in Figure 5 in detail in Section 6.2.

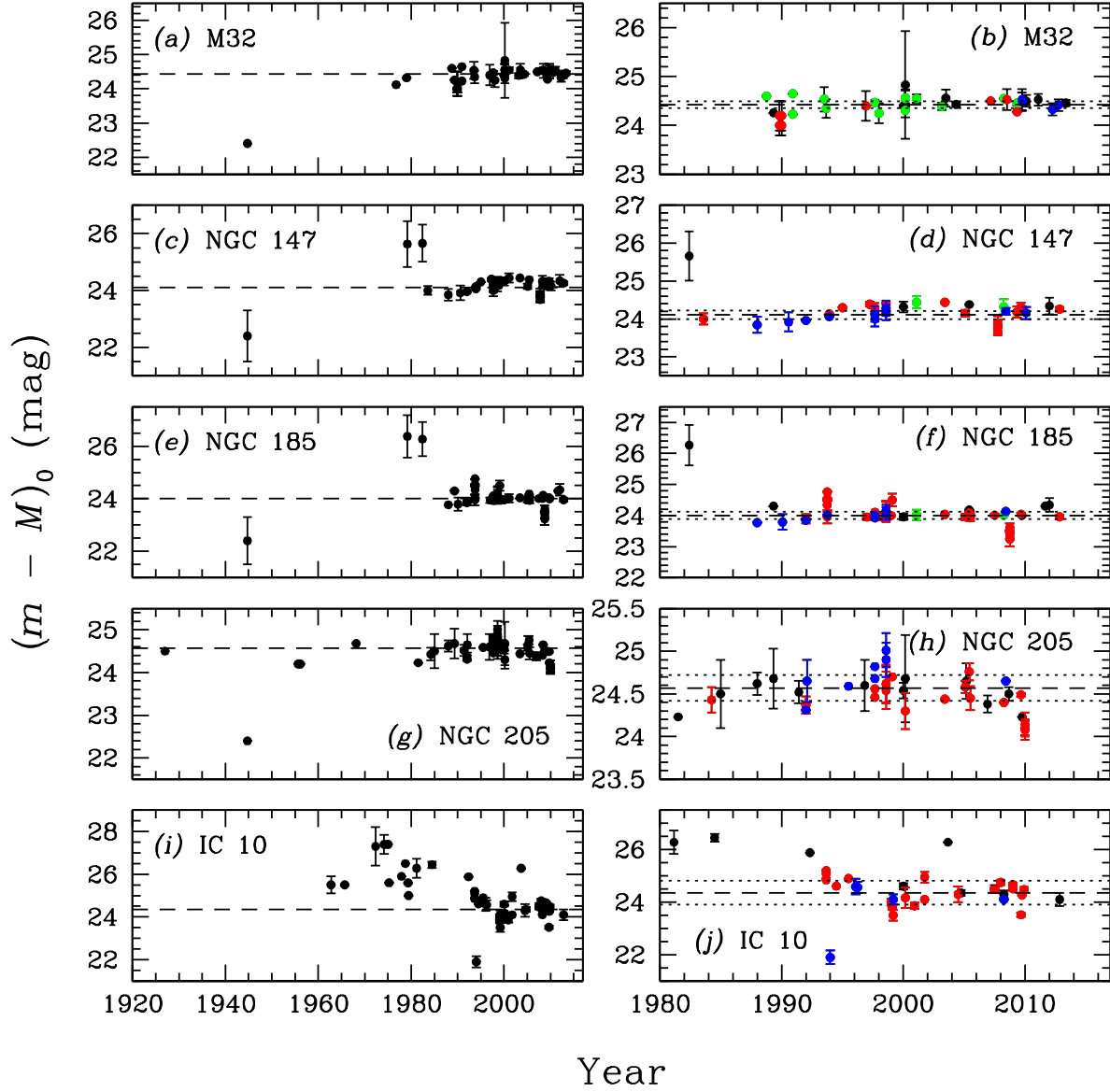


Fig. 5.— As Figure 1, but for (a) and (b) M32, (c) and (d) NGC 147, (e) and (f) NGC 185, (g) and (h) NGC 205, and (i) and (j) IC 10. (left) Full chronological trends in distance determinations for each of our sample galaxies. (right) Zooms of the more recent timeframe since 1980. Red: TRGB-based estimates. Blue: RR Lyrae-based distance determinations (Cepheid-based distances for IC 10). Green: SBF distances. The horizontal dotted lines represent the  $1\sigma$  uncertainties on the weighted mean distance moduli (for IC 10, they reflect the uncertainties in the TRGB-based distances).

## 6. Verdict

### 6.1. A consensus M31 distance modulus

In Section 4 we pointed out that one needs to carefully correct the M31 distance determinations to define a common distance scale. We discussed the nature of these corrections and showed the results in Figure 3 and Table 1. Although the scatter among the modern, post-2001 values in Table 1 is non-negligible, the combination of all 34 post-2001 values pertaining to the Cepheid and RR Lyrae variables (corrected to a common LMC distance modulus of 18.50 mag), as well as the TRGB distances, leads to a robust M31 distance modulus of  $(m - M)_0^{\text{M31}} = 24.46 \pm 0.10$  mag. The post-2001 and post-2005 averages for the Cepheid and RR Lyrae variable stars, as well as those for our TRGB comparison sample, comfortably fall within the mutual uncertainty ranges. At the distance of M31, the line-of-sight location of the individual distance tracers with respect to the galaxy’s midplane is negligibly affected by depth issues, except for members of the M31 GC system. This latter effect is exemplified by the spread in distance moduli among the galaxy’s GCs as determined by Rich et al. (2005), Perina et al. (2009), and—to a lesser extent (because of the smaller number of GCs included)—Mackey et al. (2006): see Figure 2 (bottom right-hand panel). We note in passing that Clementini et al.’s (2009) robust distance measurement to the M31 GC B154— $(m - M)_0^{\text{B154}} = 24.52 \pm 0.08$  mag—is formally consistent with the consensus distance modulus derived here. This was, in fact, the first robust distance derivation that was based on distance determinations to a large sample of 89 RR Lyrae variables in a single M31 GC. The offset between both measurements most likely reflects the GC’s position at a distance that is slightly greater than that to the galaxy’s center. This is supported by the spread in GC distances implied by the results of Rich et al. (2005), Mackey et al. (2006), and Perina et al. (2009).

Salaris & Cassisi (1998) reported a systematic difference between their distance moduli—based on a theoretical calibration of the TRGB magnitude using the models of Salaris & Cassisi (1997)—and the Cepheid-based empirical distance scale of Lee et al. (1993), which is based on observations of Galactic GCs hosting RR Lyrae stars. They found that the TRGB scale yields longer distances by 0.12 mag; the offset does not seem to depend on metallicity. Salaris & Cassisi (1998) suggest that this systematic difference underscores the need for a revision of the zero point of the Cepheid distance scale. On the basis of the average distance moduli listed in Table 1, we find a systematic difference of the same order, 0.08–0.10 mag, for the post-2005 average distance moduli (although we note that this may be owing to small-number statistics). Mochejska et al. (2000) explored the effects of blending of Cepheids with intrinsically luminous stars in the disk of M31 using a combination of ground- and space-based (*HST*) images (see also Vilardell et al. 2007). They concluded that the



Cepheid distance scale *pertaining to M31* requires a 9% upward adjustment to counteract crowding effects, which is approximately twice the systematic difference found both by Salaris & Cassisi (1998) and in this paper (Table 1).

It is instructive to compare our recommended M31 distance modulus of  $(m - M)_0^{\text{M31}} = 24.46 \pm 0.10$  mag with the most “direct” distance moduli obtained to date. In the latter case, we refer to the geometric distances based on observations of EB systems. The most recent distance estimates to M31 based on EBs yield distance moduli ranging from  $(m - M)_0^{\text{M31}} = 24.44 \pm 0.12$  mag (Ribas et al. 2005) to  $(m - M)_0^{\text{M31}} = 24.36 \pm 0.10$  (Vilardell et al. 2010a,b). We note that the most recent value, which is based on a combination of the individual distance determinations to two EB systems, is somewhat smaller than our recommended value (although still within the mutual  $1\sigma$  uncertainties). This is again reminiscent of the situation we encountered for the LMC in Paper I, where the EB distances based on hot, early-type were systematically smaller than those resulting from cool, late-type (and longer-period) EBs. We attributed this to the more significant systematic uncertainties affecting the hotter systems (cf. Pietrzyński et al. 2013).

Finally, we comment on the recent determination of the distance modulus to M31 by Riess et al. (2012),  $(m - M)_0^{\text{M31}} = 24.38 \pm 0.06$  (statistical)  $\pm 0.03$  (systematic) mag. These authors highlight their high-precision result, with an unprecedented total uncertainty of 3%. However, in the context of the discussion in Section 4, we point out that they adopted a distance scale corresponding to an LMC distance modulus of  $(m - M)_0^{\text{LMC}} = 18.40$  mag. While their precision may indeed be unprecedented, to fit on the distance scale that has emerged in the course of our work—and on which we report in both Paper I and here—their corrected distance modulus is  $(m - M)_0^{\text{M31}} = 24.48 \pm 0.07$  mag (total uncertainty). This comfortably falls within the  $1\sigma$  uncertainties of our recommended value.

## 6.2. Self-consistent distances to the M31 group

Distance determinations to M33 exhibit a large spread compared with other satellites of the M31 group. The full range spans some 30% with respect to the mean and depends on the type of distance indicator. A robust distance estimate was recently published by the Araucaria Project (Gieren et al. 2013) based on the NIR PLR defined by two dozen long-period classical Cepheids. They derived a true distance modulus  $(m - M)_0^{\text{M33}} = 24.62 \pm 0.03$  (statistical)  $\pm 0.06$  (systematic) mag and a reddening of  $E(B - V) = 0.19 \pm 0.02$  mag. These same authors provide a detailed analysis of the uncertainties that might affect these estimates, including their dependence on metal abundance (Bono et al. 2010; Bresolin 2011), crowding, and—in particular—reddening estimates. The latter seem to represent a thorny

problem, since recent estimates based on either an O-type EB (Bonanos et al. 2006) or blue supergiant stars for which individual spectroscopic determinations were obtained (U et al. 2009) yield reddening estimates that differ by a factor of two. M33 is the only “dwarf” spiral in the Local Group and there is no doubt that it is a very interesting laboratory to constrain possible systematic errors affecting both old (e.g., RR Lyrae variables) and young (e.g., Cepheids) solid distance indicators.

In Table 2, we provide the statistical properties of the distances to M33 and IC 1613 resulting from our key tracers, split into decade-long time intervals. The exact period ranges adopted for these intervals are not important; our aim here is to check whether there may have been significant shifts in the “best” distance moduli for both galaxies since the early 1990s. The “best-fitting” distance moduli indicated by the horizontal dashed lines in Figure 4 are the weighted means from the most recent period considered in Table 2. The differences between the weighted mean distance moduli for each of our three tracer populations in the period since 2000 are smaller than the relevant  $1\sigma$  uncertainties.<sup>7</sup>

It is instructive to compare our recommended distance moduli for M33 and IC 1613—i.e.,  $(m - M)_0^{\text{M33}} = 24.67 \pm 0.07$  mag and  $(m - M)_0^{\text{IC 1613}} = 24.34 \pm 0.05$  mag—with those implied by alternative methods of distance determination that have not contributed to these “best” values. For M33, we have access to a number of “direct,” geometric methods ( $H_2O$  masers: Argon et al. 2004; Brunthaler et al. 2005; *O-type EB*: Bonanos et al. 2006; Bonanos 2007, 2008; note that these latter values are not independent). Figure 4c shows that our recommended distance modulus for the galaxy is encompassed by the error bars of all geometric methods. Similarly, a comparison of the post-2000 distance moduli and their published uncertainties, derived based on fits to CMD features (*RC*: Kim et al. 2002; Orosz et al. 2007; *CMD fits*: Barker et al. 2011), the Tully–Fisher relation (Tully et al. 2008), and the high-luminosity cutoff to the planetary nebulae luminosity function (PNLF; Magrini et al. 2000; Ciardullo et al. 2004), shows good agreement within the statistical uncertainties. On the other hand, two types of distance tracers lead to systematic differences in their resulting best values, although both pertain to only a single publication each: the long-period variable calibration of Pierce et al. (2000) leads to a systematic difference of order  $2\sigma$ , while the novel flux-weighted gravity–luminosity relation also leads to a systematically larger distance estimate (cf. U et al. 2009) at the  $2\text{--}3\sigma$  level.

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<sup>7</sup>Note that the apparent “trend” for M33 of increasing distance modulus from Classical Cepheids to RR Lyrae variables and the TRGB is opposite that for IC 1613. This, combined, with the  $\sim 1\sigma$  variation among the mean distance moduli for all three tracer populations, indicates that these “trends” are not physically real (because in many cases the calibration relations underlying the results were similar or the same) but simply reflect persistent statistical uncertainties.

Table 2: Statistical properties of the key M33 and IC 1613 distance measurements. Distance moduli based on Cepheid and RR Lyrae variable stars have been calibrated to the “canonical” LMC distance modulus,  $(m - M)_0^{\text{LMC}} = 18.50$  mag. Means and population standard deviations are given in units of magnitudes.

		M33		IC 1613	
		00/1990 – 12/1999	00/2000 – 12/2013	00/1990 – 12/1999	00/2000 – 12/2013
Classical	Mean	24.620	24.573	24.410	24.360
Cepheids	$\sigma$	0.157	0.188	0.011	0.107
	$N$	10	25	6	59
RR Lyrae	Mean	24.680	24.677	24.291	24.341
	$\sigma$	0.116	0.114	0.121	0.062
	$N$	6	7	8	6
TRGB	Mean	24.833	24.698	24.407	24.289
	$\sigma$	0.128	0.108	0.068	0.118
	$N$	6	13	6	17
Weighted	Mean	<b>24.719</b>	<b>24.671</b>	<b>24.409</b>	<b>24.336</b>
	$\sigma$	<b>0.075</b>	<b>0.072</b>	<b>0.011</b>	<b>0.049</b>

For IC 1613 the three post-2000 distance estimates based on RC magnitudes (Dolphin et al. 2001, 2003; Udalski et al. 2001) are fully consistent with our recommended value. We also point out that Scowcroft et al. (2013) derived a weighted average of 57 distance estimates from the NASA Extragalactic Database (NED) that is consistent with our result, i.e.,  $(m - M)_0^{\text{IC 1613}} = 24.33 \pm 0.07$  mag, although the NED data set is incomplete at the time of writing and their approach does not allow control of population-specific systematic uncertainties, as we have attempted here.

In Table 3 we offer statistical insights into the robustness and internal consistency of the distance determinations to each of remaining five dwarf galaxies for the key tracer populations. We also provide the weighted-mean, recommended distance moduli for further use, where we have taken into account the number of data points contributing to each mean tracer-based distance estimate, the intrinsic spreads in those determinations, and the individual error bars pertaining to the published values. The variable star-based distance moduli have been rescaled to reflect an LMC distance modulus of  $(m - M)_0^{\text{LMC}} = 18.50$  mag. Again, we adopted the period since 1990 (and until the end of December 2013) as our “modern” timeframe for further analysis. For IC 10, we adopted as “best” distance modulus that based on the TRGB only because of the unusually large scatter in the Cepheid-based distances published for this galaxy since 1990.

We have indicated the  $1\sigma$  uncertainty levels on the weighted mean distance moduli in the right-hand panels of Figure 5 (using the mean TRGB as a proxy of the weighted mean for IC 10). The uncertainties are small for M32, NGC 147, and NGC 185. For M32, the most obvious outliers are two low TRGB-based distance estimates from Freedman (1990), who provided their best estimates for the distance to M32 based on two different identifications of the TRGB level (determined using the brightest and second brightest discontinuities in the luminosity function of the red giant branch), at  $(m - M)_0^{\text{M32}} = 24.0$  mag and 24.2 mag, respectively. Based on our analysis of the metadata for M32, we recommend a “best” distance modulus of  $(m - M)_0^{\text{M32}} = 24.43 \pm 0.07$  mag. This recommendation is also supported by the three independent RC-based distance estimates published for the galaxy (Worthey et al. 2004; Fiorentino et al. 2010; Monachesi et al. 2011), yielding a mean of  $\langle (m - M)_0^{\text{M32}} \rangle = 24.49$  mag and a  $1\sigma$  uncertainty of 0.04 mag. The data point with the large error bar in Figure 5b is based on calibration of the bright cutoff of the PNLFF (Ferrarese et al. 2000), yielding  $(m - M)_0^{\text{M32,PNLFF}} = 24.83 \pm 1.10 \pm 0.13$  (systematic) mag. We note that, because of the close association of M32 with and its projection onto the disk of M31, until the dynamical modeling of Byrd (1976), all previous articles that needed to adopt a distance to M32 simply took the galaxy to be located at the distance of M31.

The published distance moduli for both NGC 147 and NGC 185 have reached an approx-

Table 3: Statistical properties of the key distance measurements to the additional five Local Group dwarf galaxies covering the timeframe from 1990 until the end of 2013. Distance moduli based on Cepheid and RR Lyrae variable stars have been calibrated to the “canonical” LMC distance modulus,  $(m - M)_0^{\text{LMC}} = 18.50$  mag. Means and population standard deviations are given in units of magnitudes.

Galaxy	Tracer	Mean	$\sigma$	$N$
M32	SBF	24.451	0.133	12
	TRGB	24.318	0.201	6
	RR Lyrae	24.443	0.088	4
	<b>Mean</b>	24.430	0.069	
NGC 147	TRGB	24.155	0.223	17
	RR Lyrae	24.098	0.120	9
	<b>Mean</b>	24.111	0.106	
NGC 185	TRGB	24.027	0.333	26
	RR Lyrae	23.993	0.128	8
	<b>Mean</b>	23.997	0.119	
NGC 205	TRGB	24.447	0.200	18
	RR Lyrae	24.701	0.214	8
	<b>Mean</b>	24.565	0.146	
IC 10	<b>TRGB</b>	24.355	0.451	20
	Cepheids	23.852	1.117	5

imately stable level in recent years. Notable outliers occurred, however (NGC 147: Kang et al. 2009, only provided as an abstract; NGC 185: Sohn et al. 2008). Both articles, published by a subset of the same authors, provided TRGB-based estimates that were systematically lower than the long-term average values. These systematically smaller distance estimates may be owing to a combination of the authors’ use of the Yonsei–Yale isochrones for their calibration instead of the more often used Padova isochrones and their NIR  $JHK$  calibration instead of the more customary  $I$ -band (or equivalent) calibration. This difference gives, therefore, a useful quantitative indication as regards the remaining systematic uncertainties in (red) optical versus NIR TRGB calibration. For both galaxies, post-1990 independent distance tracers—such as those based on SBFs, horizontal-branch stars (Han et al. 1997; Butler & Martínez-Delgado 2005), ( $K$ -band) long-period variables (Lorenz 2011; Lorenz et al. 2011, 2012), and kinematics-based methods (Devereux et al. 2009)—lead to estimated distance moduli that are fully consistent with our weighted means.

Figures 5g–j (and in particular panels h and j) show that the distance estimates to NGC 205 and IC 10 continue to be subject to larger fluctuations among published values. Their distance estimates appear to have converged to some extent in the recent past, however. The clear, systematically low set of distance outliers for NGC 205 were published by Jung et al. (2009), whose results deviate to a similar extent from the bulk of the measurements and the long-term average,  $(m - M)_0^{\text{NGC 205}} = 24.57 \pm 0.15$  mag, as the estimates of Kang et al. (2009) and Sohn et al. (2008) for NGC 147 and NGC 185, respectively. The Jung et al. (2009) article shares a large subset of the same authors and is based on the same approach as these other two papers. In addition, where Devereux et al. (2009) found distances in line with the long-term average for NGC 147 and NGC 185, for NGC 205 their distance estimate is systematically lower, at  $(m - M)_0^{\text{NGC 205}} \sim 24.23$  mag, than the long-term average. This may indicate lingering systematic effects caused by peculiar motions due to the dominant presence of M31.

Among the M31 satellite galaxies, IC 10 plays a key role, since it is a very actively star-forming galaxy. It is, in fact, considered the only analog to the so-called “post-starburst” dwarf galaxies in the Local Group (Gil de Paz et al. 2003). However, it is located at low Galactic latitude, and its photometry is severely affected by foreground extinction. This partially explains the broad range in distance estimates associated with IC 10. These range from  $(m - M)_0^{\text{IC 10}} = 23.5 \pm 0.2$  mag ( $D \simeq 0.5$  Mpc), based on application of the TRGB method (Sakai et al. 1999), to well beyond the Local Group using the PNLf (Jacoby & Lesser 1981),  $(m - M)_0^{\text{IC 10}} = 26.28 \pm 0.45$  mag ( $D \simeq 1.8$  Mpc). A similarly significant scatter is seen in relation to the galaxy’s reddening estimates, which range from  $E(B - V) = 0.8$  mag (Richer et al. 2001) to  $E(B - V) = 1.2$  mag (Sakai et al. 1999). More recently, Sanna et al. (2008)—using a new calibration of the TRGB method and very accurate *HST*/Advanced Camera for

Surveys photometry—derived new estimates of both the distance,  $(m-M)_0^{\text{IC } 10} = 24.56 \pm 0.08$  (statistical)  $\pm 0.08$  (systematic) mag, and the galaxy’s reddening,  $E(B-V) = 0.78 \pm 0.06$  mag. This, in turn, supports additional extant evidence that IC 10 is a likely member of the M31 subgroup.

Indeed, the set of distance estimates to IC 10 shows a larger number of outliers with respect to the long-term average than the other M31 group members discussed above, although a consensus distance seems to have been reached in the period since 2000. In this most recent period, one TRGB-based distance (Kim et al. 2009) is clearly discrepant (i.e., low) with respect to the mean. A second discrepant (i.e., large) distance is, in fact, an *upper limit* resulting from PNLF analysis (Magrini et al. 2003). More recent PNLF-based determinations (Kniazev et al. 2008; Gonçalves et al. 2012) are fully consistent with the weighted mean for this galaxy. Other notable distance tracers in the post-2000 period, particularly those based on carbon stars (Demers et al. 2004; Vacca et al. 2007), are also in line with our expectations for the bulk of the data set.

### 6.3. The bigger picture

We are now in a good position to make a series of recommendations for the use of robust distance measurements to a set of key Local Group galaxies. We provide a summary of our basic recommendations, based on both Paper I and the present work, in Table 4.

In Figure 6 we compare our set of benchmark distances to our sample of Local Group galaxies with those from a number of recent distance compilations. Because TRGB-based distances are the common denominator among all of our sample galaxies, we show both the weighted mean distance moduli derived in this paper (and in Paper I for the LMC) and those based on the TRGB in the respective sample galaxies. For comparison, we also show the mean levels and the  $1\sigma$  spreads in distance modulus implied for all galaxies. It is clear that all comparison data sets exhibit significant scatter in the relative distance moduli between many possible choices of pairs of sample galaxies, even considering the published error bars.<sup>8</sup> We remind the reader that our weighted means (as well as the TRGB-based distances) are based on the largest data set of distance measurements available to date, with particular emphasis on converging trends in more recent years and a careful analysis of the contributions from the different tracer populations. The data set that exhibits the closest match to our set of benchmark distances is that published by McConnachie (2012), although

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<sup>8</sup>Note that Tammann et al. (2008) adopted a generic, generous uncertainty of 0.15 mag for all of their weighted mean distance moduli.

Table 4: Recommended distance moduli (as a function of increasing distance) to selected Local Group galaxies, comprising a robust local framework.

Galaxy	$(m - M)_0^{\text{best}}$ (mag)	Tracer(s)	$(m - M)_0^{\text{TRGB}}$ (mag)	Ref. <sup>a</sup>
LMC <sup>b</sup>	$18.49 \pm 0.09$	Cepheids, RR Lyrae, CMD	18.54–18.69	I,*
NGC 185	$24.00 \pm 0.12$	TRGB, RR Lyrae	$24.03 \pm 0.33$	II
NGC 147	$24.11 \pm 0.11$	TRGB, RR Lyrae	$24.16 \pm 0.22$	II
IC 1613	$24.34 \pm 0.05$	Cepheids, RR Lyrae, TRGB	$24.29 \pm 0.12$	II
IC 10	$24.36 \pm 0.45$	TRGB	$24.36 \pm 0.45$	II
M32	$24.43 \pm 0.07$	SBF, TRGB, RR Lyrae	$24.32 \pm 0.20$	II
M31	$24.45 \pm 0.10$	Cepheids, RR Lyrae, TRGB	$24.47 \pm 0.01$	II
NGC 205	$24.56 \pm 0.15$	TRGB, RR Lyrae	$24.45 \pm 0.20$	II
M33	$24.67 \pm 0.07$	Cepheids, RR Lyrae, TRGB	$24.70 \pm 0.11$	II
NGC 4258	$29.29 \pm 0.08$	H <sub>2</sub> O masers	29.24–29.44	H99,*

NOTES:

<sup>a</sup> I, II: Papers I, II; H99: Herrnstein et al. (1999; see text); \* Various authors have determined TRGB-based distances to the LMC and NGC 4258. The ranges in distance moduli reflect the body of published work since 2000. LMC measurements based on the TRGB magnitude were published by Romaniello et al. (2000), Sakai et al. (2000), and Bellazzini et al. (2004); NGC 4258 measurements include Mouhcine et al. (2005), Rizzi et al. (2007), Mager et al. (2008), and Madore et al. (2009).

<sup>b</sup> All variable star-based distances reported in this table have been rescaled to the recommended LMC distance modulus determined in Paper I,  $(m - M)_0 = 18.49 \pm 0.09$  mag. In practice, this has only affected (through a shift by  $-0.01$  mag) the “best” distance moduli to M31 and NGC 205.



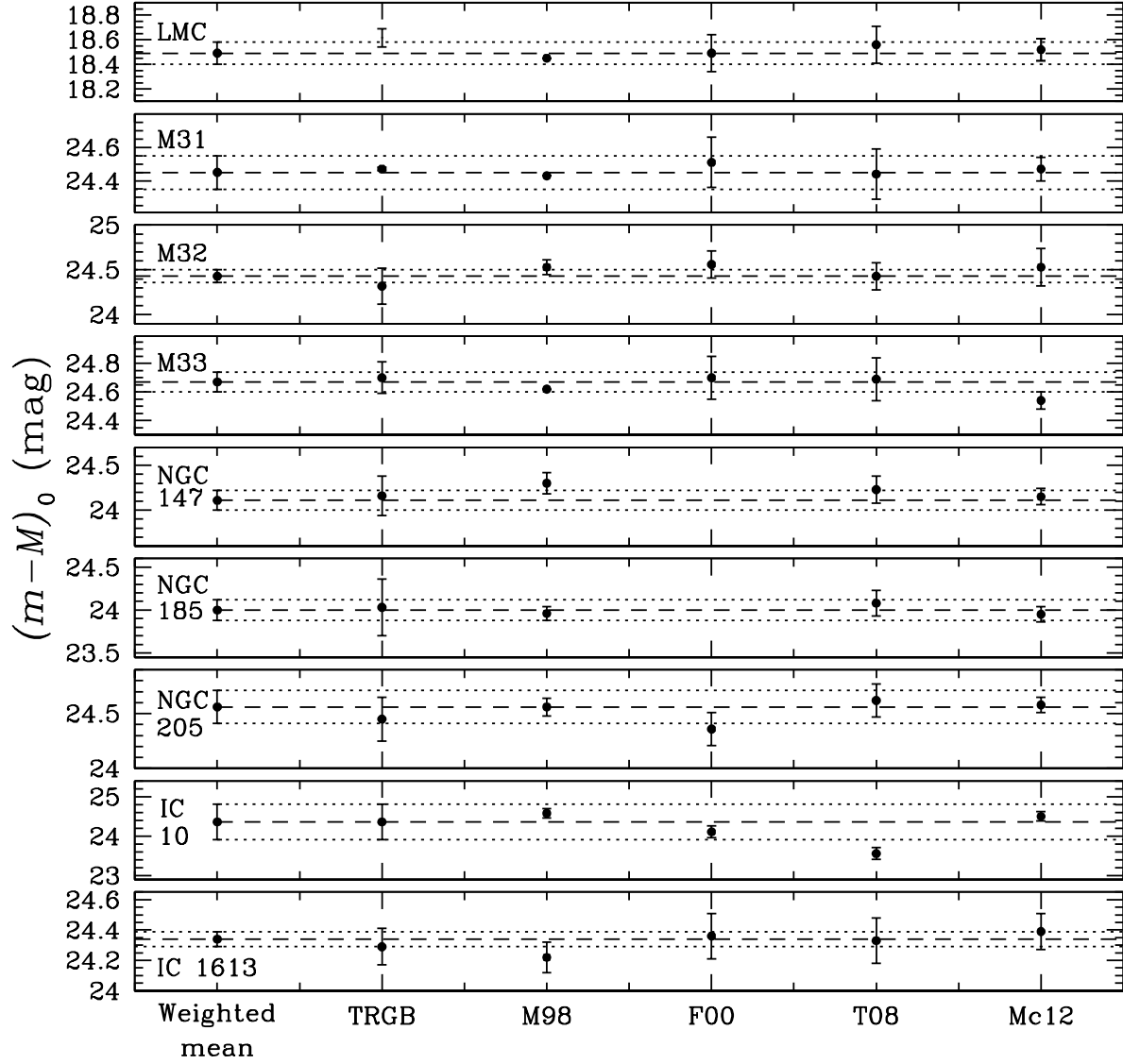


Fig. 6.— Comparison of our set of benchmark distances to the sample of Local Group galaxies (indicated in the individual panels) discussed in this article with those from a number of recent distance compilations. “Weighted mean” and TRGB: this work, except where indicated in Table 4; M98: Mateo (1998); F00: Ferrarese et al. (2000); T08: Tammann et al. (2008); Mc12: McConnachie (2012).

his distance to M33 is significantly shorter than our recommended value. Through the body of work presented in both Paper I and the present article, we aimed at providing an updated, robust set of benchmark distances. Given our adopted approach, the recommended values therefore supersede those suggested in the context of older compilations, which were often based on smaller metadata samples and earlier calibration attempts.

Going to near- and mid-IR wavelengths may enable us to reduce the uncertainties in the distances to Local Group galaxies. At present, 2–3% distance accuracy is already achievable to the LMC, and this may be improved to  $\sim 1\%$  in the near future! For instance, the Carnegie Hubble Program, using data from the warm *Spitzer* mission, derived  $(m - M)_0^{\text{LMC}} = 18.477 \pm 0.034$  mag (Freedman et al. 2012). Meanwhile, Ripepi et al. (2012) used NIR *VISTA* observations to arrive at  $(m - M)_0^{\text{LMC}} = 18.46 \pm 0.03$  mag and Inno et al. (2013) found  $(m - M)_0^{\text{LMC}} = 18.45 \pm 0.02$  (statistical)  $\pm 0.10$  (systematic) mag based on optical/NIR PLR analysis of a large sample of fundamental-mode LMC Cepheids. These distances are comfortably close to and within the mutual uncertainties of the direct, geometric distance determination based on eclipsing binaries by Pietrzyński et al. (2013),  $(m - M)_0^{\text{LMC}} = 18.493 \pm 0.008$  (statistical)  $\pm 0.047$  (systematic) mag.

Water maser measurements, which were first applied to NGC 4258 (Herrnstein et al. 1999; see also Table 4), have been extended to other nearby systems. Initial efforts to determine the distance to M33 have thus far resulted in  $D_{\text{M33}} = 750 \pm 140 \pm 50$  kpc— $(m - M)_0^{\text{M33}} = 24.38^{+0.49}_{-0.64}$  mag (total uncertainty)—where the first uncertainty in the linear distance determination is related to uncertainties in the HI rotation model adopted for the galaxy, and the second uncertainty comes from the proper motion measurements (cf. de Grijs 2013).

The technique of Very Long Baseline Interferometry is also increasingly used to measure extragalactic proper motions. In turn, this enables geometric distance determination out to some 100 Mpc, including to the nearby galaxies NGC 4258, M33, UGC 3789, and NGC 6264. Combined with *a priori* information on a galaxy’s inclination with respect to our line of sight and its rotation curve, based on radial velocity measurements, we can construct an accurate, slightly warped “tilted-ring” model of the galaxy’s dynamical structure, usually assuming circular orbits (although this assumption does not result in major systematic uncertainties). This, in turn, allows correlation of the angular proper motion measurements with the rotational velocity information obtained in linear units and, thus, provides an independent distance measurement.

Simultaneously, the Megamaser Cosmology Project (e.g., Reid et al. 2009, 2013; Braatz et al. 2010) aims at using extragalactic maser sources to directly measure  $H_0$  in the Hubble flow, which is clearly a very challenging endeavor at distances in excess of 100 Mpc! Their

preliminary results look promising, however: using NGC 6264 ( $D = 144 \pm 19$  Mpc) as a benchmark, they find  $H_0 = 68 \pm 9$  km s<sup>-1</sup> Mpc<sup>-1</sup> (Kuo et al. 2013), which is indeed very close to the current best determinations of  $H_0$  based on a variety of independent measures. This thus looks like a promising way forward to eventually build a robust distance ladder out to the Hubble flow.

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